

1

HIGH-SPEED LASER ARRAY DRIVER

CROSS-REFERENCE TO RELATED APPLICATION(S)

The present application claims the priority of U.S. Provisional Application No. 60/252,838 entitled "High-speed Laser Array Driver," filed November 22, 2000, the contents of which are fully incorporated by reference herein.

FIELD OF THE INVENTION

The present invention relates most generally to the field of optical transmission of information. More particularly, the present invention relates to an integrated circuit apparatus and method for driving lasers to maintain desired optical of lasers while reducing power consumption.

15

BACKGROUND OF THE DISCLOSURE

In the field of telecommunications, lasers such as vertical cavity surface emitting lasers (VCSELs) and other opto-electronic devices are commonly used for the transmission of information along optical fibers and the like. VCSELs, in particular are especially desirable in today's optical communication systems because they are efficient, small in size, readily assembled into arrays, and easy to manufacture.

Within optical communication systems utilizing VCSELs or other lasers, it is often desirable to control the parameters of the optical data signal being transmitted. For example, it is often desirable to control average power and amplitude of the signal. If the average power P_{ave} is maintained properly, the laser may be modulated about the average power bias point at a modulation level necessary to achieve desired high and low light output power levels, P_{high} and P_{low} .

An optical modulation amplitude (OMA) and an extinction ratio (ER) of the laser, defined as $P_{high} - P_{low}$ and P_{high}/P_{low} , respectively, is commonly maintained within predetermined limiting values to maintain desired optical signal integrity. The limit values commonly are per specification such as the

1 Synchronous Optical NETWORK (SONET) or Gigabit Ethernet specification, or any other specification that the system is designed to meet.

Therefore, in order to obtain reliable and repeatable
5 results in many fiber optic transmission applications, it is desirable to maintain both the average signal power and the OMA (or ER) within predetermined limit values. Unfortunately, laser characteristics change during the operation of the laser. In particular, as a laser such as a VCSEL is used to transmit
10 optical data, the temperature of the operating laser and the environment which contains it, typically tends to increase, which may degrade laser performance. The OMA also changes as the temperature of the operating environment changes, and the change of the OMA with temperature is typically dependent on the
15 particular laser used and the age of the particular laser. For example slope efficiency, a measure of optical output per current used to drive the laser, of the lasers may change due to temperature and age of the lasers. Automatic power control may be used to ameliorate these problems. Automatic power control
20 is also used to account for laser threshold changes.

Similar to many other electronic systems, it is desirable to limit the power used by the laser drivers to drive the lasers. The limiting of the power used by the laser drivers to drive lasers result in reduction to power requirements and also reduces
25 heat dissipation. Due to the reduced heat dissipation, the reduction in power requirements may also result in improvement of the laser performance due to reduced increase in temperature.

SUMMARY OF EMBODIMENTS OF THE INVENTION

30 In one embodiment of the present invention, a power down feature is provided to disable one or more unused lasers so as to reduce power dissipation.

In another embodiment, a dual feedback system is used to provide feedback signals for the adjustment of modulation and bias currents delivered to a single laser or each laser in a laser array through the respective laser drivers. In this

1 manner, the dual feedback system may be used to maintain average
optical power and Optical Modulation Amplitude (OMA) within
predetermined limit values. The feedback signals may be provided
by one of the data lasers or by an additional control laser that
5 operates at a lower frequency than the data lasers.

In yet another embodiment of the present invention, a
transistor base leakage is used to emulate a large resistance
element to result in a long time constant without the use of a
large capacitor or large resistance.

10 In yet another embodiment of the present invention, a split
power supply is provided to provide a lower supply voltage to a
portion of a circuit, thus reducing power consumption of the
overall circuit.

15 In yet another embodiment of the present invention, a low
off-voltage is selected for a laser driver for driving longwave
VCSELs.

20 In yet another embodiment of the present invention,
feedback is used to reduce baseline wander and Inter Symbol
Interference (ISI) that are produced by a low frequency dip
appearing in the frequency response observed when using a PNP
current source in conjunction with an NPN differential stage to
drive a laser. A feedback resistor is employed in the PNP
current mirror to substantially flatten the dip present in the
frequency response.

25

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood from the
following detailed description, when read in conjunction with the
accompanying drawings. It is emphasized that, according to
30 common practice, the various features of the drawings are not to-
scale. On the contrary, the dimensions of the various features
are arbitrarily expanded or reduced for clarity. Included in the
drawings are the following figures:

FIG. 1 is a generalized schematic laser driver array block
diagram;

1 FIG. 2 is a generalized schematic block diagram showing an integrated circuit with laser power down feature;

FIG. 3 is a generalized schematic block diagram showing I_{mod} and I_{bias} adjustment currents generated using a photodiode, peak
5 detector and a average power circuit;

FIG. 4 is a combination circuit and block diagram showing the dual feedback loop in an embodiment of the present invention;

FIG. 5 is a block diagram illustrating another laser feedback loop embodiment of the present invention;

10 FIG. 6 is a block diagram illustrating yet another laser feedback loop according to an embodiment of the present invention;

Figs. 7A, 7B and 7C are graphical diagrams illustrating the effect of photodiode capacitance on a received optical signal;

15 FIG. 8 is a graphical illustration of the accumulation of charge in an optical detector with respect to the data pattern received;

FIG. 9 is a generalized schematic block diagram of input circuitry of a peak-to-peak detector, which includes transistors
20 configured to result in a sufficiently long discharge time;

FIG. 10 is a generalized schematic block diagram showing a dual power supply according an embodiment of the present invention;

FIG. 11 is a simplified circuit diagram of a low off-
25 voltage laser driver for longwave VCSELs according to an embodiment of the invention;

FIGs. 12A and 12B are graphical illustrations of pulse shaping and baseline wander problems as may be caused by a low frequency dip.

30 FIGs. 13A and 13B are schematic diagrams illustrating the use of feedback in a PNP current mirror source to reduce baseline wander and ISI according to one embodiment of the present invention.

1 DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

I. Overview

One embodiment of the present invention provides an apparatus and method to control both the average power and optical modulation amplitude (OMA) of laser signals driven by an array of laser drivers. The apparatus and method may be used to drive a single laser using a single laser driver or an array of lasers. The laser drivers in such a driver array may be integrated on a single integrated circuit. Other embodiments of the present invention are directed to providing power savings to the laser driver (or the laser driver array in case of driving multiple lasers) and to maintaining desired parameters of the optical output signals. Embodiments of the present invention may be particularly useful in high-speed applications, such as, for example, ones having 2.5 GBPS (Giga Bits Per Second) data rates.

Embodiments of the present invention may also support systems having lower or higher data rates than 2.5 GBPS. In an exemplary embodiment, the lasers may be shortwave or longwave VCSELs but it should be understood that embodiments of the present invention also apply to other lasers, such as, for example, edge emitting lasers.

FIG. 1 is a block diagram of a laser driver 100, which may include one or more embodiments of the present invention. The laser driver 100 may be implemented on a single integrated circuit chip, but may also be implemented in two or more separate integrated circuit chips. The laser driver 100 typically has an operating temperature range of 0-85C, but it may operate at other temperatures as well. The laser driver 100 may include one or more of the following features which are described in detail below: 1) Laser Power Down Feature; 2) Dual Feedback Laser Driver Implementation for Use with Low Bandwidth Photodetectors, using either a control laser or a data laser for feedback; 3) Slow Discharge Implementation by Use of Transistor Base Leakage; 4) Laser Driver Split Power Supply 2.5/3.3 Volt Feature; 5) Low Off-Voltage Laser Driver for Longwave VCSELs; and 6) Feedback to

- 1 Reduce Baseline Wander and Inter Symbol Interference (ISI) for
Low Bandwidth PNP source.

As shown, the laser driver 100 includes a differential data driver 102, a laser current controller 104 and a high-speed
5 current driver 106. It should be understood, however, that the laser driver 100 as illustrated is exemplary only, and the laser driver 100 may include one or more other components to perform laser driving functions in conjunction with the components illustrated in FIG. 1. For example, the laser driver 100 may be
10 used to drive a single laser or multiple lasers, which may be organized into a laser array. When the laser driver 100 is used to drive multiple lasers, for example, the laser driver 100 may include multiple high-speed current drivers, one for each of the multiple lasers. However, even when multiple high-speed current
15 drivers are used, only one laser current controller need be used to provide modulation and bias currents to the multiple high-speed current drivers. By avoiding duplication of the circuitry for overhead functions that may be implemented in a single circuit, e.g., the laser current controller, additional power
20 savings may be realized.

To provide the modulation and bias currents to the high-speed current driver 106, the laser current controller 104 receives a set bias current (Set I_{bias}) signal and a set modulation current (Set I_{mod}) signal. The laser driver 100 may
25 work in an open loop mode where the set bias current signal and the set modulation current signal are used to set bias and modulation currents, respectively. The set bias current signal may be used to set the bias current, for example, to 4 mA or 6 mA. The set modulation current signal may be used to set the
30 modulation current.

In one embodiment of the present invention, the laser driver array may also work in a feedback loop mode, which may also be referred to as an automatic power control (APC) mode, to adjust the modulation and bias currents. Upon assertion of an APC enable signal received by the laser current controller 104, the laser driver 100 may operate in the feedback mode in which

1 the modulation and bias currents are adjusted based on one or more feedback signals (not shown).

The high-speed current driver 106 receives differential data signals, DIN and DINB from the differential data driver 102, and converts them into an appropriate current signal, using the bias and modulation currents, to drive the corresponding laser.

A single-ended driver may be used instead of the differential driver in some embodiments. When multiple high-speed current drivers are used to drive multiple lasers, multiple differential data drivers provide differential data signals to the multiple high-speed current drivers.

The laser driver 100 may further includes a disable feature using a disable signal to disable the laser when the laser is not used, further reducing power consumption. The disable signal may be provided to the high-speed current driver 106. When the laser driver includes a laser driver array implemented on a single integrated circuit chip to drive multiple lasers, the disable feature allows the laser driver to selectively drive lasers, in an array of lasers, separately. If the integrated circuit is designed to drive 12 VCSELs, for example, a quad disable signal may be used to turn off four of the laser drivers, allowing the integrated circuit to drive an array of 8 VCSELs. The capability to turn off one or more laser drivers may be referred to as an IC laser power down feature, or as a laser power down feature.

25

II. Laser Power Down Feature

One embodiment the present invention includes a laser driver array for driving a laser array in the present includes a power down feature as illustrated in FIG. 2. The power down feature is typically implemented in an integrated circuit that includes a laser driver array. The laser driver array 200 includes a first laser driver control circuit 204 and a second laser driver control circuit 206. The laser driver array 200 also includes a power down select switch 202. The first laser driver control circuit drives, by providing I_{bias} and I_{mod} currents, lasers 1-8 represented by a laser 208. Similarly the

1 second laser driver control circuit drives, by providing I_{bias} and I_{mod} currents, lasers 9-12 represented by a laser 210.

The first laser driver control circuit 204 is coupled directly to a power supply voltage V_{cc} . However, the second
5 laser driver control circuit 206 is coupled to the power supply voltage V_{cc} via a power down select switch 202. A power down select signal is provided to the power down select switch to open and close the switch 202. When the switch is closed, the power supply voltage V_{cc} is provided to the second laser driver control
10 circuit, allowing it to drive four lasers, lasers 9-12, in addition to the lasers 1-8. When the switch is open, however, the second laser driver control circuit is not powered. With this option for controlling power to one or more laser drivers, power may be saved while less than all the laser drivers in the
15 laser driver array are needed to meet laser driving needs for low power dissipation applications. At the same time, availability of the additional laser driving capability allows for a flexible design so that a single IC design may be used for multiple applications.

20 In the laser driver array 200, there are total of twelve laser drivers, four of which may be turned off and on with the power down select switch. In other embodiments, there may be more or less than twelve laser drivers in the laser driver array.

In addition, the number of lasers that may be switched off and
25 on may be different. For example, the laser driver array may include eight, twelve or any other suitable number of laser drivers. Further, other embodiments may include more than one power down select switch to switch more than one group of laser drivers on and off.

30 The laser power down feature may be applied to various different types of laser drivers including but not limited to longwave VCL (vertical cavity laser) array drivers, shortwave VCL array drivers and edge emitting laser array drivers. In many system applications, use of a single part rather than multiple different parts having different number of laser drivers in the laser driver array may result in cost reduction and reduction of

1 manufacturing process needs due to production of greater volume
for a single part.

5 III. Dual Feedback Laser Driver Implementation for Use with Low Bandwidth Photodetectors

Bias and modulation currents I_{bias} and I_{mod} are typically fed to a single laser driver to drive a single laser or to multiple laser drivers to drive multiple lasers. The bias current I_{bias} given a constant modulation current, will affect the average power, P_{ave} , of the optical signal emitted by the laser. The modulation current I_{mod} typically modulates the optical power signal above and below the average power level to provide peak-to-peak amplitude. It is often desirable to maintain an average power P_{ave} as well as optical modulation amplitude (OMA), typically defined as $P_{high} - P_{low}$, or extinction ratio (ER) of the laser, typically defined as P_{high}/P_{low} , within predetermined limit values in order to insure proper operating parameters. It should be understood that when OMA falls within the predefined range, in accordance with relevant specifications, for example, ER commonly also falls within an acceptable range, since the OMA and ER are related to one another.

As the operating temperature of the laser increases, the slope efficiency, typically defined as the laser current-to-optical power ratio, commonly decreases. As the temperature of the environment including the laser increases, the bias current needed to produce a given average optical power typically also changes. Specifically, the slope of the laser current-to-optical power ratio decreases, and more current is typically used to produce a given change in optical power. Furthermore, the change in slope as a function of temperature varies from laser to laser, and the slope for a given laser varies with the age of the laser.

In one embodiment of the present invention, I_{bias} and I_{mod} currents are adjusted using dual feedback loops, one for each of the I_{bias} and I_{mod} currents, to maintain laser power within predetermined limit values to compensate for changes to laser characteristics due to such factors as the operating temperature

1 and the age of the laser. FIG. 3 is a generalized schematic
block diagram showing a laser signal 250 sensed by a
photodetector 252 which may be a photodiode. The terms
photodiode and photodetector may generally be used
5 interchangeably. FIG. 3 illustrates the general principle used
for adjustment of the I_{bias} and I_{mod} currents using the feedback
loops.

The signal from the photodetector is fed to a circuit 254,
which includes a peak-to-peak detector 256, and an average power
10 detector 258. The peak-to-peak detector and the average power
detector are used in their respective feedback loop to adjust the
modulation current I_{mod} and the bias current I_{bias} , respectively.

In this scheme, the laser signal 250 is the output of the laser
that is being adjusted by the adjustments to the I_{bias} and I_{mod}
15 currents. Therefore, the laser signal in this circuit is fed
back into the circuit to make the laser output power adjustment.

In embodiments of the present invention, use of the dual
feedback loops to adjust the laser output power may also be
referred to as an Automatic Power Control (APC) and Automatic
20 Modulation Control (AMC).

FIG. 4 is a circuit/block diagram showing a dual feedback
loop in one embodiment of the present invention. In the
embodiment shown in FIG. 4, a laser driver array 300 is
implemented on a single integrated circuit (IC). In other
25 embodiments, more than one integrated circuit may be used to
implement the laser driver array. In still other embodiments,
the dual feedback loop may be used with only a single laser
driver for driving a single laser.

The laser driver array 300 includes laser drivers 324. The
30 laser drivers 324 include twelve laser drivers for VCSEL 01
through VCSEL 12. The twelve laser drivers in the laser driver
array 324 may be referred to as data laser drivers for VCSEL 01
through VCSEL 12. The laser driver array also includes a 13th
laser driver 328, which is used as a control laser driver for
VCSEL 13. VCSEL 13 is referred to as a control VCSEL or as an
extra VCSEL.

1 In the laser drivers 324 of FIG. 4, the 13th laser driver
328 is a control laser driver, however, in practice, any one of
the twelve laser drivers in the laser drivers 324 may be used as
a control laser driver. The lasers, which may be driven, are not
5 limited to VCSELs, and in other embodiments, other lasers such
as edge emitting lasers may be used. In still other embodiments,
some or all of the laser drivers may be external to the
integrated circuit. Furthermore, the thirteen VCSELs illustrated
are intended to be exemplary only and other numbers of data and
10 total VCSELs may be included in alternative embodiments. In some
embodiments data lasers may be used to provide feedback, thus
eliminating the need for a control laser and a control laser
driver.

The laser driver array 300 provides for Automatic Power
15 Control (APC) feedback or open loop operation and the ability to
switch between the two modes. The second feedback mechanism is
an automatic modulation control (AMC). The dual feedback control
system is used to provide an adjustment to both the bias current
and the modulation current fed to the laser drivers. The laser
20 driver array 300 includes a bias feedback loop for adjusting the
bias current based on average optical power detection. The bias
feedback loop includes a bias feedback path 304. The laser
driver array 300 also includes a modulation feedback loop for
adjusting the modulation current based on peak-to-peak detection.
25 The modulation feedback loop includes a modulation feedback path
302. A signal accumulation capacitor C_{pk} may be used to set the
discharge time constant for the peak-to-peak detector. The
signal accumulation capacitor C_{pk} may be integrated with the
integrated circuit 300, or it may be implemented as an external
30 capacitor.

Light emitted from either the control laser or one of the
data lasers is monitored using the photodetector 308 and a
transimpedance amplifier (TIA) 310. The TIA 310 is used in the
modulation current feedback path to adjust the modulation current
 I_{mod} , while the amplifier 316 is used in the bias feedback path
to adjust the bias current I_{bias} . According to one exemplary

1 embodiment, the laser driver for each of the lasers within the array is included within an integrated circuit. According to another exemplary embodiment, the laser drivers may be external to the integrated circuit.

5 The bias and modulation currents, I_{bias} and I_{mod} , respectively, are used to set the lasers at room temperature and are programmed from a temperature stabilized voltage reference. The I_{bias} and I_{mod} currents may be adjusted through the selection of one set resistor for all lasers in the array. From the laser control, an adjusted bias current 332 and an adjusted modulation current 334 are generated, and each is fed to each laser driver of the array of laser drivers 324 as well as the control laser driver 328. The photodetector 308 may be disposed in proximity to one of the data lasers VCSEL 01 through VCSEL 12 or the control laser (VCSEL 13) depending on the exemplary embodiment used. More particularly, the photodetector 308 may be configured to absorb light emitted from the VCSEL that is situated proximately to the photodetector. FIG.4 shows that the singular detected bias and modulation currents are used to adjust the I_{bias} and I_{mod} signals 332 and 334 respectively, provided to each of the VCSELs 01-13.

The laser driver array 300 of FIG. 4 is illustrated as receiving two feedback lights, a data laser feedback light and a control laser feedback light. Generally, only one of the feedback lights may be implemented and used. For example, one embodiment may use only the control laser feedback while another embodiment may use only the data laser feedback.

A. Use of Control Laser Feedback Loop

30 Conventional photodetectors used in feedback systems for optical communication systems typically have capacitance that tends to slow down data detection, so that P_{high} and P_{low} may not be detected properly on a real-time basis for high-speed optical communication systems. Thus, laser drivers that use feedback for adjusting output optical modulation amplitude generally use high-speed photodetectors which are typically difficult to assemble

1 and costly to manufacture. If a laser that is driven at a slower
speed may be used to provide feedback signal, slower
photodetectors may be used. The slower speed photodetectors are
typically easier to assembly and less costly to manufacture.

5 In this embodiment of the present invention, an extra laser
is used as a control laser to provide average optical power and
peak-to-peak information and to provide for the adjustment of the
modulation current and the bias current delivered to each of the
data laser drivers of the laser driver array 324 to control the
10 average optical power and optical modulation amplitude (OMA).

As illustrated in FIG. 4, a control laser driver circuit
306 is used to drive the control laser, VCSEL 13. The VCSEL 13
may have substantially the same operating characteristics as
those of the other VCSELs of the array, such as VCSELs formed on
15 the same substrate. The control laser driver circuit 306
includes a 100 MHz oscillator 326 and the laser driver 328. The
100 MHz oscillator may provide the modulation to the laser driver
328 to drive the control laser. In other embodiments, the
oscillation frequency of the oscillator may be more or less than
20 100 MHz. Since the oscillation frequency of 100 MHz is generally
much lower than the data rate commonly used in optical
communication systems, such as, for example, 2.5 GBPS (Gigabits
per second). Since the control laser operates at a lower
frequency photodetectors having lower frequency responses may be
25 used.

FIG. 5 is a block diagram 500 illustrating an arrangement
of data lasers and a control laser in an exemplary laser array
502. In other embodiments, the control laser may be used with
varying numbers of data lasers, including a single laser. The
30 control laser in FIG. 5 is illustrated as the 13th laser, however
the distinction is arbitrary and any laser may be used as the
control laser. The same I_{bias} and I_{mod} currents, used to drive the
data lasers within the array, also drive the control laser.

Depending on the laser used, any of a direct, reflection,
or rear exit feedback configuration may be used for the
photodetector and TIA arrangement to provide feedback as to the

1 laser output power. For the case of the rear exit feedback
configuration, the optical power feedback is commonly
proportional to the light from the primary emission. For
example, when edge emitting lasers or long wavelength VCSELs
5 emitting at 1.3 microns are used, the rear exit configuration may
be used since light is transmitted out of each of the opposing
ends of the laser. The other feedback configurations illustrated
may be used as well. For another example, for a non-long
wavelength VCSEL, a direct or reflection configuration may be
10 used depending on the environment within which the control laser
is formed.

As shown in each of FIGs. 4 and 5, an oscillator (100 MHz
oscillator 326 or the oscillator 506) is used to provide a signal
to the control laser. The signal has a significantly lower
15 frequency than the data signal delivered to the data lasers. For
example, in a 2.5 GBPS system, the signal provided to the control
laser may be on the order of 50 MHz - 150 MHz. This signal may
include substantially the same amplitude and power but is
transmitted at a lower speed.

20 According to this exemplary embodiment, the capacitance of
the photodetector, which is typically a limiting factor in high-
speed applications because it does not allow the photodetector
to charge and discharge quickly enough for the peak-to-peak
amplitude to be detected. By using a lower frequency signal,
25 such as the 50 MHz - 150 MHz signal of the present embodiment a
lower frequency response photodetector may be used. It is
typically advantageous to use the lower frequency photodetector
because they are generally easier to build than high-speed
photodetectors, which commonly must be built smaller to limit
30 their capacitance. Further, for the high-speed photodetector to
operate successfully, the TIA typically may need to be placed in
proximity to the photodetector itself, and not integrated into
the IC.

Since the control laser operates at a significantly lower
frequency, the average optical power and the peak-to-peak optical
power may be determined for the control laser on a real time

1 basis, instead of having to wait for a suitable data pattern so
that these parameters may be detected. The average optical power
and the peak-to-peak optical power may then be provided in a
timely fashion to the feedback loops which adjust the modulation
5 and bias currents.

The control laser is useful in high-speed application such
as Gigabit Ethernet applications or other applications where
repeated bit streams are limited in number such that low speed
photodetectors are not practical to detect average and peak to
10 peak values for feedback purposes. The capability to use slower
photodetector diodes may result in simplified assembly and
manufacture, which in turn may lead to reduction in cost. The
lower frequency parameter detection also requires reduced high-
speed considerations such as impedance matching, transmission
15 lines, and issues associated with parasitic capacitance,
inductance, etc. Further, the capability to operate at low
frequency may simplify the use of the TIA, allowing it to be
located further away from its photodiode and placed in an IC with
less power dissipation than would otherwise have been required.

20 The laser driver array may support various different
signaling formats including but not limited to SONET (Synchronous
Optical Network) that uses pseudo random signal formats as well
as Gigabit Ethernet and other applications that do not use pseudo
random signal formats. The embodiment using the control laser
25 supports applications that do not use pseudo random signal
formats as well as those that do. However, for applications that
use pseudo random signal formats, a data laser may be used
instead of the control laser to provide feedback signals to
adjust I_{mod} and I_{bias} . Use of the data laser instead of the
30 control laser eliminates the need to supply power to the control
laser, and thus results in reduced overall power requirements.

B. Use of Data Laser for Feedback

One of the data lasers may be used to provide feedback in
one embodiment of the present invention when the application is
for a system with pseudo random signal formats, such as, for

1 example, SONET, a commonly used network used in optical
communication equipment. In this embodiment, the control laser
may be disabled to reduce power dissipation by using a control
laser select signal provided to the control laser driver circuit
5 306. This embodiment may be used with other data formats other
than SONET. It may work with any system for dealing with pseudo
random data, anything that allows for a long string of 1's
sufficient to allow a photodetector used with the system to reach
substantially a peak value of the signal. The data is not
10 required to be pseudo random if a sufficient number of successive
1's are periodically present. If a sufficient number of
successive 1's are periodically present a photodetector may reach
substantially the peak value (and a sufficient number of
successive 0's are present to allow the photodetector to
15 discharge to the level corresponding to a logical zero light
intensity). Statistically a sufficient number of repeated bits
are necessary to allow the photodetector to charge or discharge to
levels representative of limit values. The present embodiment,
however, will be described in detail primarily in reference to
20 a SONET system for illustrative purposes.

SONET specifications are commonly prescribed and used in
optical communication systems. A SONET data signal is a pseudo
random signal which provides a high statistical probability that
a sufficient number of consecutive bits will be present and
25 therefore may be received and accumulated within a parasitic
capacitance of the photodetector to allow the photodetector to
charge to a maximum (and discharge to a minimum) value even for
very high-speed applications. A bit may be a "1" or a "0".
Although the following discussion will refer to bits as "1's" and
30 will discuss the accumulated charge associated with having a
sufficient number of repeating "1s" (high power level) in a data
sequence, it should be understood that the same applies to
repeating "0s" (low power level) in a data sequence. In other
words though a sequence of "1s" will be used to illustrate the
photodetector charging to a maximum value, a sequence of "0s" is

1 equivalently necessary to discharge the photo detector to a minimum value.

FIG. 6 shows an exemplary arrangement for the embodiment in which one of the data lasers is used to provide the feedback
5 signal. It can be seen that the photodetector (PD) arrangement may be a reflection arrangement or a rear exit arrangement, which have been discussed above in reference to FIG. 5. The use of the data laser to provide feedback typically does not provide for direct monitoring of the optical signal from the data laser
10 because the optical signal is transmitted to an optical medium and any direct monitoring would necessarily attenuate or otherwise compromise the transmitted signal. Therefore, one of reflection and rear exit arrangements commonly are used. The TIA used may be a low power TIA.

15 FIGS. 7A-C illustrate the effect that the photodetector capacitance may have upon a propagated optical signal. FIG. 7A shows a general case in which a photodetector is modeled as a low pass filter (LPF) receiving a waveform representing a laser signal. It can be seen that the rise and fall times of the peak-
20 to-peak signal have been increased, as the high frequency components of the signal are attenuated. FIG. 7B shows the effect of low capacitance, high bandwidth photodetectors and shows that the peak-to-peak amplitude is approximated, even though the limited bandwidth still results in somewhat slower
25 rise and fall times than the original signal. Such high frequency response photodetectors are difficult and expensive to make and are not therefore commercially practical. FIG. 7C shows the effect on a laser signal of a low bandwidth, high capacitance photodetector. It can be seen that the peak-to-peak information
30 regarding the signal is generally lost, as the photodetector does not have the high frequency response necessary to produce a good approximation of the original signal.

In SONET and other pseudo random signal generation applications, it is assumed that the pseudo random data signal provides a statistical probability that a sufficient number of repeating "1's" in a data sequence will be provided to allow a

1 capacitance of a photodetector to charge sufficiently to
approximate the peak value of the signal. An example of a
sufficient number of consecutive "1s" being received to allow a
photodetector to charge to essentially a maximum value is shown
5 in FIG. 8. If a sufficient number of consecutive 1's are
received to charge a capacitor to approximately the peak value,
a representation of that peak can be obtained using a
photodetector operating at a lower speed than the transmit data
rate.

10 The data sequence shown in FIG. 8 is intended to be
exemplary only, and various other data sequences can be obtained
in SONET and other pseudo random signal generation applications.

It should be understood that SONET and other pseudo random
signal generation applications may insure statistically that a
15 sufficient number of "1's" in a data sequence will be provided
to accumulate and provide an approximation of the peak amplitude.

Accordingly an integrated circuit may be designed to provide for
fast charging and slow discharging to assure that the statistical
probability of repeating "1's" will allow sufficient charge
20 accumulation to produce a signal of approximately the maximum
amplitude, thus assuring accurate peak value detection.

For example, in order for an approximation of a full
amplitude signal to be detected, the time constant for the
discharge time should be controlled. Configuring the discharge
25 time at a sufficiently large value by providing a high resistance
and/or high capacitance, in the discharge circuitry, increases
the discharge time constant of the circuit. A peak-to-peak
detection circuit with a long discharge is illustrated at 312 in
the laser driver array 300 of FIG. 4. In one embodiment, the
30 capacitance of the signal accumulation capacitor C_{pk} 330 in
FIG. 4 may be maintained at a sufficiently high value. As
discussed above however a high capacitance will limit the high
frequency response and so it is preferable to produce a long time
constant by increasing resistance rather than capacitance.
Additionally higher capacitance tends to require increased
integrated circuit real estate.

1 Thus, one of the data lasers operating at high-speed, e.g.,
2.5 GBPS, may be used for feedback when single or array lasers,
including but not limited to shortwave and longwave VCSELs for
SONET or other signal formats using pseudo random data transfer,
5 or signal formats with sufficient number of repeating data bits,
are used. The capability to use slower photodetector diodes may
result in simplified assembly and manufacture, which in turn may
lead to reduction in cost. The operations at lower frequency
also typically reduces the need to resolve issues related to
10 impedance matching, transmission lines, and issues associated
with parasitic capacitance, inductance, and the like.

Further, the capability to operate at low frequency may
allow for the use of simplified TIA located further away from
photodiode. Such a TIA may be placed in IC and dissipate less
15 power than otherwise would be required. In addition, through the
use of the slow discharge implementation, SONET or other
applications using pseudo random signal formats may be supported
without the added power dissipation required by an additional
control laser.

20 IV. Slow Discharge Implementation by Use of Transistor Base Leakage

The slow discharging may also be realized through use of
high resistance in the peak-to-peak detector. Returning now to
25 FIG. 4, when a resistor is used in the peak-to-peak detector 312
to form a RC-circuit with the C_{pk} 330, longer discharge times may
be realized by using higher value resistors. Therefore,
increasing the resistance of the resistor coupled to the signal
accumulation capacitor C_{pk} may also increase the discharge time.

30 However, it is often undesirable or impractical to implement a
high value resistor in an integrated circuit due to space and
other limitations. Additionally high resistances may be
difficult to control accurately in fabrication.

Therefore, in one embodiment of the present invention, the
high resistance of the resistor is simulated by using transistor
base current, which may be provided in accordance with the

1 circuitry of a peak-to-peak detector 700 shown in FIG. 9. Of
course, a peak-to-peak detector may include other components, and
the input circuitry shown in FIG. 9 is for illustrative purposes
only. The peak-to-peak detector 700 includes an input 702 via
5 which the peak-to-peak detector receives an output of the
feedback photodetector via a TIA. The input 702 is provided to
a base of an illustrative NPN input transistor 704. An emitter
of the input transistor provides output voltage V1 at a base of
a discharge time control transistor 706. The output voltage V1
10 depends on the photodetector voltage, which is provided as an
input 702 via a TIA.

An emitter of the input transistor 704 provides the current
to charge the capacitor 710. The base of the discharge time
control transistor 706 provides the discharge path for capacitor
15 C_{pk} 710. The input transistor 704 serves as a rectifier/diode of
the electrical signal received from the photodetector. Since
transistor 706 is limited to an emitter current of
(illustratively) 35 μ Amps the base leakage current of transistor
706 is limited to a value equal to the emitter current divided
20 by β , the current amplification of transistor 706. Accordingly
the base current of transistor 706 is limited to 35 μ Amps/ β , that
is a small value that generally results in a relatively long
discharge time, thus providing a similar effect as adding a large
resistor.

25 The signal accumulation capacitor C_{pk} 710 controls discharge
time according to the equation $I = C_{pk} dv/dt$. C_{pk} may be on the
order of 5.5 pf but other capacitance values may be used
alternatively. The current source 708 that provides the
discharge current may supply 35 μ A or any other suitable current.

30 In summary, the use of the capacitance and the discharge current
that controls the charge and discharge time constants allows for
the accumulation of a sufficient number of consecutive "1's"
provided by SONENT or other pseudo random signal formats to enable
the peak and peak-to-peak values to be detected and provided to
the dual feedback loops.

1 Use of fixed base current to simulate high resistance is
described in reference to the specific circuit, however, it
should be noted that it is applicable to any circuit where it is
desirable to create a sufficiently long discharge time,
5 especially when addition of a high value resistor to the circuit
or large capacitance is undesirable.

V. Laser Driver Split Power Supply 2.5/3.3 Volt Feature

To further reduce power consumption, a dual power supply
10 750 may be used in one embodiment of the present invention, such
as shown schematically in FIG. 10. Two power supplies, a 2.5 V
power supply and a 3.3 V power supply, may be used to power
various parts of the laser driver array, which may be implemented
on an integrated circuit (IC). A power supply set at a nominal
15 value of 3.3 volts, for example, is used to power laser output
stage functions 754 to drive lasers 756, and a second power
supply set at a lower voltage, for example 2.5 volts, is used to
power other components 752 of the integrated circuit. The use
of the 2.5 volt power supply in parts of the integrated circuit
20 may reduce the overall power consumption of the integrated
circuit.

Thus, use of the split power supply reduces power
consumption by powering selected functions in the laser output
stage with a 3.3 Volt supply voltage and remaining function with
25 a 2.5 Volt supply. In other embodiments, an option to use either
a single 3.3 Volt supply or a split power supply of 2.5/3.3 Volt
may be allowed to a laser driver array integrated on a single IC.

The power consumption is reduced when two supplies are used.

The split power supply may be used in the laser driver array to
30 reduce power consumption. The split power supply may also be
used in any other circuit that may benefit from reduced power
consumption due to such split power system.

1 VI. Low Off-Voltage Laser Driver for Longwave VCSELs

Longwave VCSELs may or may not have an off voltage, also referred to as a low voltage, that differs from those of typical shortwave VCSELs.

5 FIG. 11 is a simplified circuit diagram of a circuit 800 for driving a laser 806. The laser 806 may be a single VCSEL or it may represent an array of VCSELs. In the IC 802, power consumption may be altered by operating at voltage levels at the driving point 804 that are appropriate for the longwave VCSEL in
10 question. Exemplary longwave VCSEL 806 has a low voltage, e.g., 1.5V or less, which is lower than the typical low voltage for an exemplary shortwave VCSEL. The circuit 800 allows direct current coupling with no AC coupling capacitor required, thus reducing PCB (printed circuit board) space requirements. The elimination
15 of AC coupling reduces power consumption by eliminating losses in the capacitor. Those of ordinary skill in the art will appreciate that the low voltage of a particular longwave VCSEL may in fact be less than, comparable to or greater than that of a typical shortwave VCSEL, and that the circuits described herein
20 may be used or modified in accordance with the voltages of the VCSEL in question.

VII. Feedback to Reduce Baseline Wander and ISI (Inter Symbol Interference) for Low Bandwidth PNP Source

25 One of the considerations that may be addressed in designing any data communication system is the shape of the waveform transmitted. A distorted waveform may not be detected correctly at the receiving end, thus resulting in error. FIG. 12A, for example, illustrates a desired waveform 810 for a data
30 communication system, such as, for example, the optical communication system embodiment of the present invention.

1 When a PNP current mirror circuit having an NPN sink, such
as the one that may be implemented with PNP transistors 824, 836
and NPN transistors 830, 838 of FIG. 13A, is used as a current
source to drive the laser (e.g. 840) an undesirable low frequency
5 dip may occur in an AC magnitude response. Such a frequency dip
is illustrated in frequency response plot 816 of FIG. 12B. The
low frequency dip may distort the waveforms. A waveform 812 of
FIG. 12A illustrates such distorted waveform, for example, at an
OC-3 data rate (155 Mbps). An eye diagram 814 of FIG. 12A
10 suffers from baseline wander, for example, at an OC-48 data rate
(2.5 Gbps) due to the low frequency dip.

The low frequency dip, such as the one in the frequency
response plot 816, may be substantially flattened by adding a
feedback resistor 862 to a PNP current mirror of the laser driver
15 circuit, such as a laser driver circuit 860 of FIG. 13B. The
resistance of the feedback resistor may be adjusted until a
desired frequency response is achieved. The circuit may be
applied to laser drivers including VCSELs. The feedback resistor
may also be added to any driver, which uses a PNP current mirror
20 source to drive a digital load, to substantially flatten the low
frequency dip.

Additionally adding a series resistor-capacitor circuit as
illustrated at 801 and 803 or 805 and 807 can lessen any
deterministic jitter at the load 840 or 880. The resistor-
25 capacitor circuit may have different values, which will vary
depending on the circuit parameters. Typical values for resistor
801 or 805 are between 100 and 300 ohms and typical values for
capacitor 803 or 807 are between 0.5 to 3.0 picofarads. The
values may be adjusted depending on implementation and circuit
30 details. The deterministic jitter and need for the feedback
resistor 822 may also be diminished by the placement of an
inductor 809 between the collector of PNP transistor 836 and the
junction of transistor 838 and the load 840.

It should be emphasized that the above-described
embodiments are intended to be exemplary only. For example, the
terms "laser" and "VCSEL" are used interchangeably to emphasize

1 that the embodiments of the present invention may find
application in optical systems using both VCSELs and other
lasers. The laser array may include copy of various numbers of
data lasers. Furthermore, the specific arrangement of the
5 components of the integrated circuit and the details of the
method generally covered by the integrated circuit, are exemplary
only. The integrated circuit including the laser driver array
of the present invention may be integrated into larger integrated
circuits including other features, without departing from the
10 scope and spirit of the inventive concepts disclosed herein.
Further, the embodiments described herein may be useful for
individual lasers as well as arrays.

15

20

25

30